17th World Conference on Nondestructive Testing, 25-28 Oct 2008, Shanghai, China

Adhesive Bond Testing By Laser Induced Shock Waves

M. ARRIGONI, S. E. KRUGER, A. BLOUIN, D. LÉVESQUE, B. ARSENAULT and J.-P. MONCHALIN

Industrial Materials Institute, National Research Council of Canada
75 de Mortagne blvd, Boucherville, Quebec, Canada, J4B 6Y4
Phone: (450) 641-5076, Fax: (450) 641-5106, e-mail: silvio.kruger@cnrc-nrc.gc.ca

M. BOUSTIE
Laboratoire de Combustion et de Détonique, UPR n° 9028, 1 avenue Clément Ader, CNRS, ENSMA, 86961 Chasseneuil Cedex, France

L. BERTHE
Laboratoire d'Application des Lasers de Puissance (UPR n° 1578 CNRS), 16 bis avenue du Prieur de la Cote d'Or, 94114 Arcueil Cedex, France

Abstract

Adhesive bonding of metal sheets presents many practical advantages when compared to other joining methods, but its application for critical components is limited by the absence of reliable nondestructive methods that can assure the bond strength of the joint. In this paper, a method based on shock waves produced by pulsed lasers is applied to the evaluation of adhesive bond strength of two aluminum plates joined with different adhesive types. Shock wave, produced by short laser pulse, propagates through the aluminum plates and adhesive layer and after reflection, can cause a delamination at the adhesive/plate interface. The laser pulse energy can be scanned to probe the adhesion strength. A good joint will be unaffected by a certain level of tensile stress whereas a weaker one will be damaged. The method is made quantitative by optically measuring the aluminum surface velocity with a Doppler or velocity interferometer. Interferometer signals first give a clear signature of damaged or undamaged interfaces. In addition, these signals can be correlated with numerical simulation in order to give an estimation of the bond strength. Results show that the proposed test is able to differentiate bond quality. The proposed testing method may help a broad adoption of adhesive bonding throughout the automotive and aerospace industries.

Keywords: adhesion test, shock waves, laser interferometry, automotive testing, aerospace testing.

1. Introduction

Adhesive bonding has been a widely used joining method for a long time, but its application for critical structural automotive and aerospace components could be greatly expanded if reliable non-destructive technique that can assure the bond strength of the joint became available. Ultrasound has been the preferential technique investigated for non-destructive testing of adhesive bonds by using both linear [1,2] and non-linear [3] methods. Evidently, the use of waves with stress levels approaching that of a destructive testing should provide more reliable results. A laser generated shock wave method has been investigated for testing of coating adhesion [4] but also adhesive bonds of composite parts [5]. In this method, a shock compressive wave is induced in the material surface that propagates and is reflected as a high amplitude release wave on the opposite surface, creating tensile stress. As this release wave propagates through the adhesive layer, its interfaces will delaminate if the tensile stress is higher than the adhesive strength. By controlling the amplitude of shock waves, the method can be calibrated to be non-destructive, except when adhesive bond strength is non compliant to specifications. In this paper, this method is applied to aluminium plates joined by adhesive bonding.

2. Experimental methods

Samples

The aluminium alloy AA 5754 (also named Al3.1MgMnCr or AlMg3) was chosen because of its wide range of applications. Samples composed of two 70 mm x 60 mm plates of aluminium, 410 µm and 500 µm thick, were adhesively bonded with the following adhesives:

- *FM1000*® epoxy manufactured by *CYANAMID*®. The adhesive was cured under controlled pressure of 0.28 MPa at 170° F during 60 minutes.
- *ESP310*®, manufactured by *Bondmaster*®. Preparation temperatures must be between 150° and 204 ° C.
- *Loctite*® *414* (L414) adhesive, which is also widely spread for home use.
- *Epoxy glue* « 5 minutes », noted E5min and distributed by *LePage – Henkel*. It is a home use adhesive that can be found in hardware stores.

Sample	Thickness top Al plate ± 5 µm	Nominal adhesive thickness (µm)	Thickness bottom Al plate ± 5 µm
Al / ESP 310 / Al	410	130	500
Al / FM1000 / Al	410	400	500
Al / L414 / Al	410	50	500
Al / E5min / Al	410	60	500

Table I : Samples presenting two aluminium plates assembled with four kinds of adhesives.

Shock experiments

The experimental set-up is composed of a shock generation laser beam on the top side of the sample and the system for detection of the mechanical waves on the opposite side of the sample

(Fig. 1). Shock generation is performed with a Nd-YAG high energy pulsed laser which provides a gaussian pulse of 2.4 J with duration of about 10 ns (at half maximum) at a wavelength of 1064 nm. It is a tabletop equipment, commercially available and able to operate at a repetition rate of 10 pulses/sec. Laser excitation is performed under water confinement regime, which allows increasing the shock pressure and its duration [6]. The laser beam is focused on the 3-layered sample, through a convergent lens, on a spot of about 2 mm of diameter. Energy losses due to the light absorption in the 3 mm thick water layer [7] and spurious reflections on optical components is about 0.5 J. In such conditions, Berthe [8] and Sollier [9] showed that the shock pressure could reach up to 5 GPa at a power density of 9 GW/cm². Shock detection is performed with a single frequency, long pulse Nd-YAG laser, which delivers 400 µs duration pulses of about 500 W peak power. The detection laser beam is focused to a 400 µm spot diameter on the sample surface, opposite to the impacted area. The light reflected or scattered by the sample is collected and brought by a large core optical fiber to the Fabry-Perot etalon interferometer which gives a signal proportional to the back surface velocity [10]. Generation and detection lasers are synchronised and the signal acquisition is trigged with a signal delivered by an avalanche photodiode detecting the laser light at the shock generation. Because of the water confinement regime, the lasers are operated in a single shot mode, which allows wiping optical components sprinkled by the confining water during the impact.

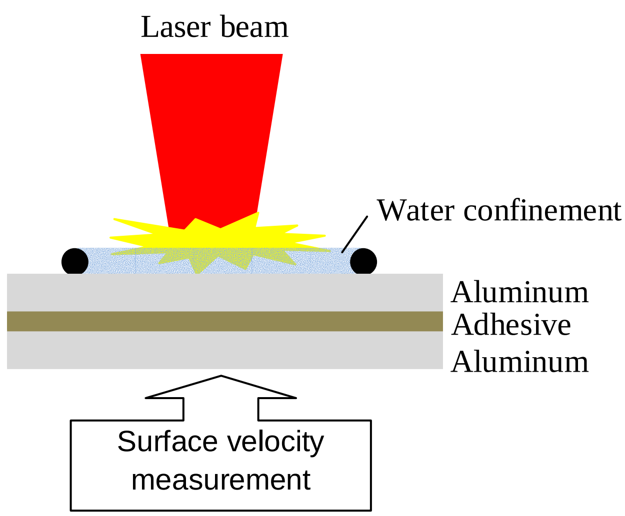


Figure 1. Experimental configuration for the shock adhesive tests.

3. Results

Delamination diagnostics

Delamination is not straightforward to diagnose by only observing the back surface velocity signals, as in the case of two layered samples [11]. For example, Figure 2a shows a signal measured on *Al/L414/Al* sample at 4.69 GW/cm² that leads to delamination and one at 2.47 GW/cm² that did not induce any delamination. From zero time (when the shock is produced) up to about 0.2 μs the shock wave propagates through the thickness of the material and its arrival at the free (opposite) surface shows a step increase of the surface velocity. The peaks that follow are reverberations on the thickness of the aluminium plates and adhesive. A clear signature of disbond may be obtained by identifying the source of each peak in these signals. This peak analysis can be made easier by using a simulation code such as *SHYLAC* [12]. *SHYLAC* is a 1D hydrodynamic Lagrangian simulation code for shocks. A comparison between experimental data and *SHYLAC* is presented in Figure 2b where a signal obtained at 4.69 GW/cm² under water-confined regime on *Al/L414/Al* sample is compared with the signal computed by *SHYLAC*. The peaks revealed by the simulation are not always distinguishable on the measured signals. To improve the delamination diagnostic, Fast Fourier Transformation (FFT) of the velocity signals was performed. The results in the frequency domain show a clear difference between a delaminated case and a sound bond case (Fig. 3).

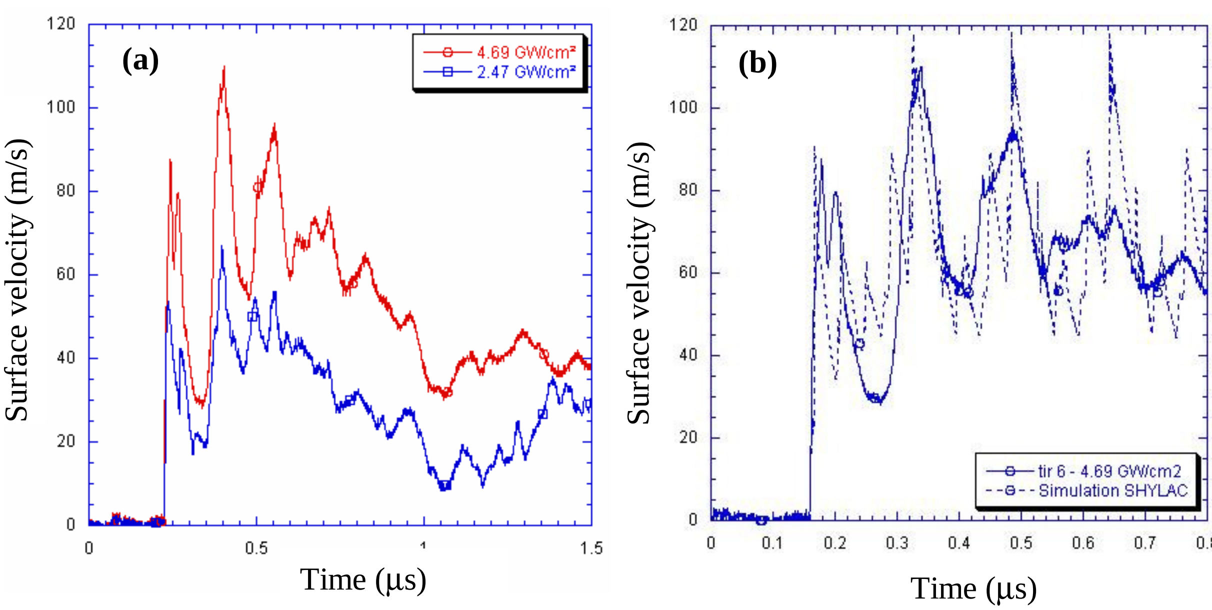


Figure 2. Opposite surface velocity for (a) two laser densities (4.69 and 2.47 GW/cm^2) and (b) experimental and simulated signals.

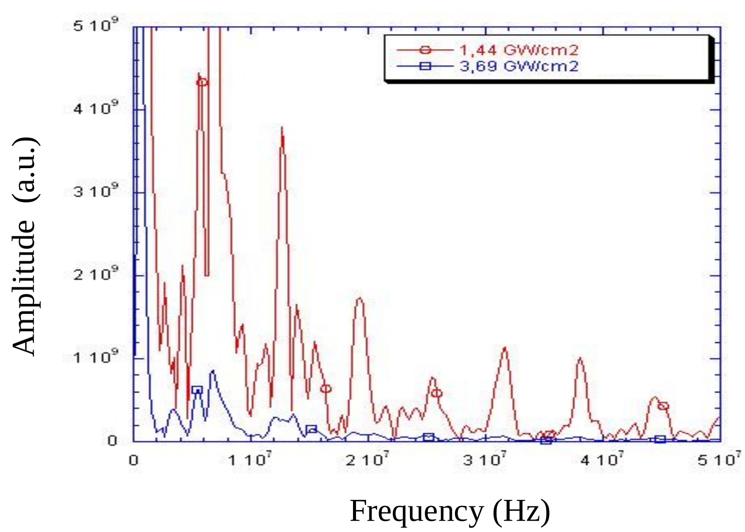


Figure 3. Spectrum of velocity signals for a delaminated (blue line) and non delaminated (red line) cases.
Actually, in each layer, there is a multitude of rebounds that interfere with already existing rebounds, having a consequence on peak amplitudes and positions. However, for a velocity signal related to a laser shot that did not lead to delamination, there are peaks after 12 MHz that are no more visible for a shot leading to delamination. These peaks are produced by consecutive rebounds in the 500 µm thick bottom Al plate and can then be observed for well bonded interface but are obviously blocked at the delaminated interface.

Ultrasonic evaluation, in a transmission configuration, has been carried out on tested samples. The signals obtained are visualized as a B-scan image (Fig. 4) that reveals delaminated areas when the ultrasonic wave is not transmitted. Shots whose power density is higher than 4.7 GW/cm² lead systematically to delamination. For the shot at 3.7 GW/cm², delamination is not visible but the FFT showed no peaks after 12 MHz whereas peaks were visible for the shot at 2.5 GW/cm². Thus, delamination induced by the shot at 3.7 GW/cm² was likely to be weak, but the interface was affected anyway.

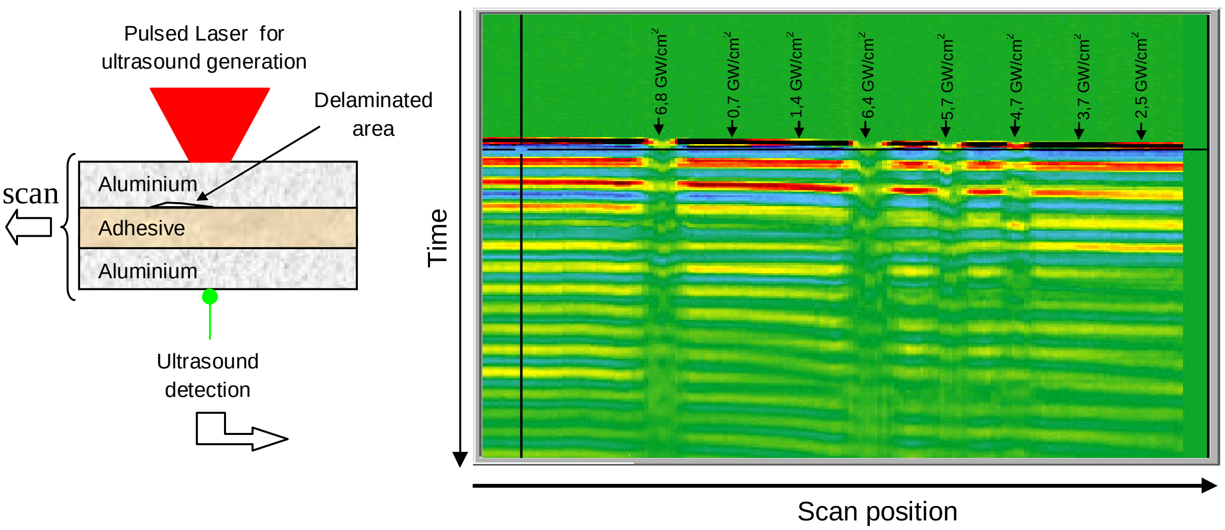


Figure 4. Laser-ultrasonic B-Scan image in a transmission configuration for the Al/FM1000/Al sample.

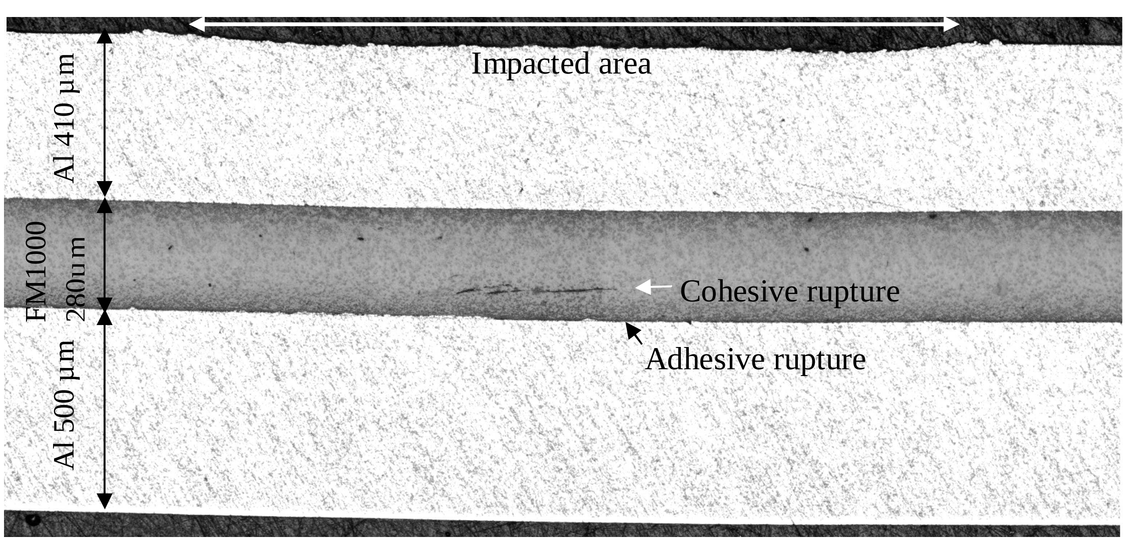
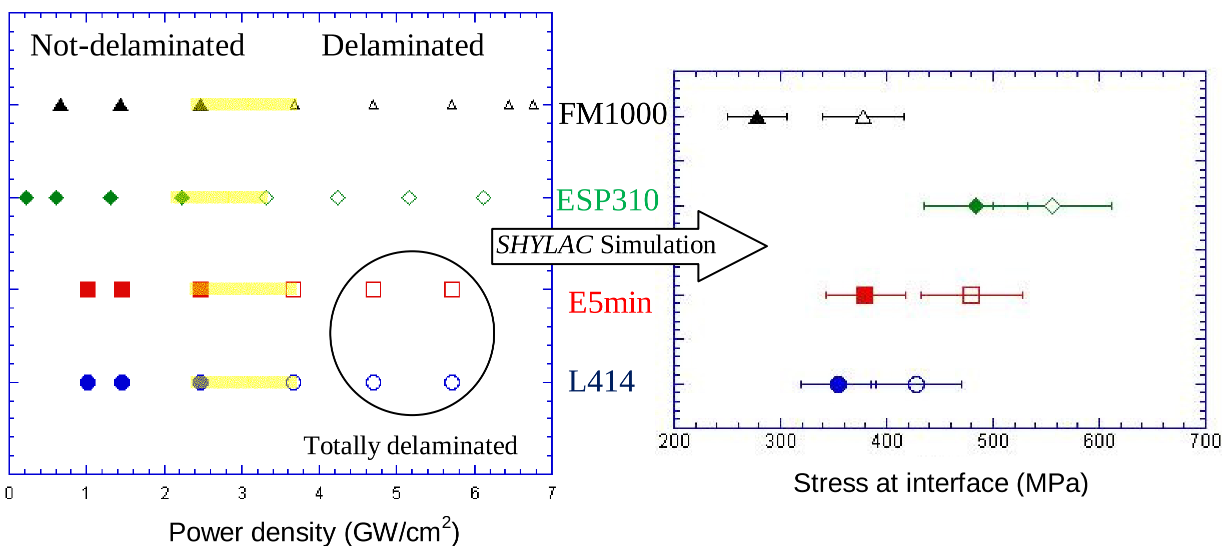


Figure 5 : Cut of Al/FM1000/Al after impact at 5,15 GW/cm^2. Cohesive rupture can be observed.

Adhesion thresholds

By using the diagnostic methods described above, the adhesive bonds of the tested samples were ranked by power density used for the tests (Fig. 6a). An empty mark represents a laser shot that lead to delamination while a full mark represents a laser shot that did not damage the sample. The laser power thresholds required to delaminate an adhesion layer are between 2.4 and 3.7 GW/cm². A difference in threshold from one sample to another is noticeable. However, samples *L414* (circles) and *E5min* (squares) were totally delaminated along the entire interface for power densities greater than 5 GW/cm². It reveals that the crack can easily propagate at the interfaces of these adhesives, whereas the *FM1000* and *ESP310* adhesive layers are not prone to large crack propagation.

Thresholds determined in GW/cm² are not convenient for representing the bond quality. Thus, for each shot, tensile stress at the adhesive/metal interface was calculated by matching *SHYLAC* simulations with experiments. Adhesion thresholds are reported in Figure 6b. The highest bond strength was the one of *ESP310* adhesive, which was estimated between 484 and 556 MPa. For *ESP310/Al* and *FM1000/Al*, bond strength measured by pull test standardised as *ASTM C633* gave respectively 65 and 69 MPa. These values obtained in quasi-static conditions are much lower than the ones determined with the shock adhesion test. Indeed, as the shock adhesion test uses dynamic loads applied for a very short time, it needs to be higher in intensity for damaging the material. This phenomenon has been also previously reported [13] for adhesion of coatings.



(a) (b)

Figure 6. a) Adhesion thresholds in GW/cm² for tested samples, with empty marks when delaminated. b) Corresponding adhesion thresholds in MPa obtained by numerical simulation with SHYLAC.

4. Conclusions

Adhesively bonded aluminium plates involving four different bond qualities made by various adhesives were tested with a laser adhesion test. The FFT analysis of free surface velocity signal allowed a diagnostic of delamination after shot, in quasi real-time. Non-destructive techniques were also applied to identify delamination locally induced by the shock test. Ultrasonic B-scan images were able to validate most of the diagnostics. From experimental signals, numerical simulations were used to estimate the tensile stress that lead to delamination. However, simulations performed with a two dimensional finite element code using more advanced constitutive laws, taking into account viscosity, temperature and porosity effects, should lead to more accurate results.

Acknowledgement

M. Arrigoni is grateful to the Canadian National Research Council for its support through the Natural Sciences and Engineering Research Council of Canada.

References

[1] S. I. Rokhlin and Y. J. Wang, Analysis of Boundary Conditions for Elastic Wave Interaction with an Interface Between Two Solids, J. Of Acoust. Soc. Am. 89 (2), pp. 503-515, (1991).

[2] D. Lévesque, et al., High Resolution Ultrasonic Interferometry for Quantitative Nondestructive Characterization of Interfacial Adhesion in Multilayer Metal/Adhesive/Metal Composites, *J. Adhesion Sci. Technol.*, Vol. 7 (7), pp. 719–741 (1993).

[3] C. Bockenheimer et al., The Method of Non-linear Ultrasound as a Tool for the Non-destructive Inspection of Structural Epoxy-metal Bonds – a Résumé, Intern. J. Of Adhesion & Adhesives 22, pp. 227-233 (2002).

[4] C. Bolis et al, Physical Approach to Adhesion Testing Using Laser-driven Shock Waves, J. Phys. D: Appl. Phys, 40, pp. 3155-3163 (2007).

[5] R. Bossi et Al, Laser Bond Inspection Device for Composites : Has the Holy Grail Been Found?, NTIAC Newsletter, Volume 30 (2), June 2005.

[6] R. Fabbro et al., Physical study of laser-produced plasma in confined geometry, J. of Appl. Phys., vol. 68 (2), p. 775-784, (1990).

[7] K. Kanyama et al., Spectral transmittance of water and sodium chloride water solution as working substance for a solar pond, Heat Transfer Japanese research, 26 (1), pp. 1-15 (1997).
[8] L. Berthe et al. J. Appl. Phys., Shock waves from a water-confined laser-generated plasma, Vol. 82 (6), pp. 2826-2832 (1997).

[9] A. Sollier et al. Eur. Phys. J. AP **16**, 131-139 (2001).

[10] M. Arrigoni et al. To be published.

[11] C. Bolis et al, Visar pull-back signals as a diagnostic for the laser adherence test applied to copper coating on aluminum substrate, , Proceedings of the 13th American Physical Society Topical Conference on Shock Compression of Condensed Matter, Portland, July 2003, pp. 1373-1376.

[12] M. Boustie and F. Cottet, Experimental and numerical study of laser induced spallation into aluminum and copper targets, J. Appl. Phys. 69 (11) pp. 7533-7538 (1991).

[13] M. Arrigoni, S. Barradas, M. Braccini, M. Dupeux, M. Jeandin, M. Boustie, C. Bolis, L. Berthe, Comparative study of three adhesion tests (EN 582 similar to ASTM C633 - LASAT (LASer Adhesion Test) - Bulge and blister test) performed on plasma sprayed copper deposited on aluminium 2017 substrates, Journal of Adhesion Science Technology, 20 (5) pp. 471–487 (2006).